SELF-COMPACTING CEMENT-BOUND PAVEMENT FOUNDATIONS FOR ROAD TUNNELS: PERFORMANCE ASSESSMENT IN FIELD TRIALS

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ABSTRACT

This paper presents the results of an experimental investigation which was carried out with the purpose of assessing the performance-related properties of self-compacting cement-bound mixtures to be employed in pavement foundations in road tunnels. The mixtures contained a significant quantity of recycled components and function-specific additives. Characteristics of the mixtures, which were produced in a concrete batch plant, were studied by means of laboratory and field tests. Investigated properties included flowability, compressive strength, resilient modulus and bearing capacity. It was found that mixtures prepared with a cement dosage of up to 100 kg/m^3 possess the required properties of flowability, strength and stiffness. On the contrary, mixtures with higher cement dosages (150 kg/m^3 and 200 kg/m^3) fail to meet all the performance-related requirements as a result of their high long-term strength which jeopardizes excavatability. Obtained results also highlighted the effects of the different components on the properties of the mixtures and led to the definition of acceptance criteria which can be adopted in actual construction works.

Keywords: cement-bound mixtures, self-compaction, pavement foundations, road tunnels, field trials

1. Introduction

In the construction of pavements in road tunnels, several options are available depending upon the factors which are considered critical by designers. On one hand, flexible pavements,

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which are constituted by bitumen-bound materials in their upper layers, offer a good solution in terms of their remarkable riding comfort, limited noise emission, easy maintenance and satisfactory performance in terms of markings visibility (EAPA 2008, Guo *et al.* 2009). On the other hand, rigid pavements, which entail the presence of an upper concrete slab, may be especially attractive as a result of their extended service life and of their better behavior in case of fire (Jofre *et al.* 2010, Puente *et al.* 2016). Other factors which may be considered when choosing pavement type include construction and life-cycle costs, availability of materials, local experience with involved technologies, and global impact on the environment (Moretti *et al.* 2016, Huang *et al.* 2015).

Whatever the selected solution, designers have to define the pavement structure in all its details, including the constitution of foundation layers comprised between the base of the tunnel and the pavement, which have the main function of providing adequate bearing capacity (Austroads 2019). Such a need, which is crucial in order to guarantee satisfactory performance, applies both to the case of tunnels with a rock substrate and those with underlying structural elements (i.e. curved inverts or linear shallow foundations).

Typical solutions which are adopted in practice involve the placement of a filling which is constituted in its bottom portion of a coarse-grained unbound material (that ensures proper drainage) and in its upper part of selected soil (that acts as a subgrade). However, as an alternative option, cement-bound materials can also be employed to form the entire filling. In particular, it may be advantageous to employ self-levelling cement-bound mixtures which can be placed without any compaction, thereafter achieving a homogeneous state even in the presence of buried underground utilities and drainage conduits. Mixtures of this type include self-compacting concrete (SCC), normally employed for the construction of structural elements (Domone 2006), and controlled low-strength materials (CLSM), which are typically used for trench backfilling operations (ACI 2013).

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Cement-bound pavement foundations in road tunnels are required to achieve a sufficient short-term bearing capacity in order to withstand the loading of construction equipment and hauling trucks within a very short time after their placement. Furthermore, laid mixtures should not develop an excessive long-term strength in order to allow excavations to be easily performed in case of maintenance needs for the buried utilities and in order to reduce the potential for reflective cracking.

By taking into consideration the requirements illustrated above, the Authors developed a mix design procedure for the formulation of self-compacting cement-bound mixtures (indicated as SC-CBMs) purposely conceived for road tunnel applications (Choorackal *et al.* 2019a, Choorackal *et al.* 2019b). These mixtures are different from standard SCCs because of their significantly lower target strength and are also different from classical CLSMs due to the fact that they contain coarse aggregate fractions. Design activities focused on mixtures containing relevant quantities of reclaimed asphalt pavement (RAP) and sludge derived from the washing of mineral aggregates employed for the production of asphalt and cement concrete mixtures. Such a choice was dictated by the need of reducing both the costs and the environmental impact associated to the production of the mixtures.

As a follow-up to initial laboratory investigations, further research studies were carried out by means of full-scale field trials which entailed the plant production and laying of several SC-CBMs. As described in this paper, the mixtures were subjected to field and laboratory tests for a comprehensive assessment of their performance-related properties.

The investigation included four field trials. Field trial 1 had the main objective of verifying the feasibility of mass production and laying of the SC-CBMs and to assess their sensitivity to variations in particle size distribution and cement dosage. As a supplement to this first trial, field trial 2 considered the use of mixtures with higher cement dosages which also included the use of an accelerating agent for the achievement of rapid hardening

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properties. Field trial 3 was similar to the previous one, except for the fact that it was actually performed inside a road tunnel in order to assess the effect of curing conditions on the in-place characteristics of this specific type of mixture. Finally, field trial 4 was carried out by considering a laying geometry which more closely replicated that of a road tunnel and by focusing on cement-bound mixtures characterized by optimized formulations identified as a result of the previous experimental activities.

Results of laboratory and field tests were interpreted with the objective of identifying the effects of the different components on the properties of the mixtures. These outcomes led to performance-related acceptance criteria which may be adopted during actual construction works which involve the use of SC-CBMs in road tunnels.

2. Materials and methods

2.1 Mixture components

Components which were available for the formation of the aggregate skeleton of the SC-CBMs were coarse sand (0-8 mm), gravel (8-18 mm), RAP (0-12.5 mm) and mineral sludge. These were subjected to preliminary characterization tests for the determination of particle size distribution and specific gravity (SG) as per corresponding EN standards (EN 933-1 and EN 1097-6). Obtained results are shown in Figure 1 and Table 1. It can be observed that the results refer to two distinct sampling operations which were carried out during the progress of the investigation. Recorded variations of the characteristics of the various components were taken into account in the formulation of the mixtures produced as part of each field trial (see section 2.2). Materials retrieved during the first sampling session were employed only in trial 1; those which were collected in the second phase of operation were used in field trials 2 to 4.

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RAP material employed in the investigation was derived from the milling of aged, dense-graded asphalt mixtures. Bitumen content of the single RAP fraction which was made available, determined as per EN 12697-39, was found to be equal to 4.57% and 4.42% (by weight of aggregates) for the material collected in the first and second sampling session, respectively. It was considered that, due to its aged conditions, residual bitumen contained in RAP would act as an inert component, with no expected diffusion through the adjacent cement paste. Nevertheless, it was not excluded that it could have some effects on the mechanical properties of the SC-CBMs (Adresi *et al.* 2017, Singh *et al.* 2019).

Mineral sludge employed in the investigation was collected from the stockpiles of an aggregate crushing plant. As a result of its origin (i.e. aggregate washing) and of its fineness, in the natural state it was characterized by a very high water content, of the order of 20%. In the initial phases of the research project (i.e. in field trials 1 and 2), the presence of such a high quantity of water was taken into account by reducing the quantity of water added during the plant production of the SC-CBMs. Nevertheless, as illustrated in the following, efforts were placed in trying to devise an appropriate system for sludge drying in order to ensure a better control of water content during mixture production and to avoid problems related to the tendency of the wet sludge to clog the feeding lines.

At first, sludge drying was attempted by simply spreading it over an open area and by periodically subjecting it to light mixing by means of a wheel loader. However, such a procedure, which was followed in preparation of field trials 1 and 2, proved to be unsuccessful, with a residual water content which remained quite high, of the order of 15%. Furthermore, it was observed that final water content was non-uniform throughout the sludge and that such a nonhomogeneity had a negative impact on the production consistency of the corresponding SC-CBMs.

A significant improvement in the drying process was achieved in the second part of the research project, when it was carried out by subjecting the mineral sludge to mechanical pulverization in the presence of added quicklime. As suggested by the wide international literature on lime stabilization of soils (Bell 1996, Jha and Sivapullaiah 2015, Rosone *et al.* 2018), it was envisioned that with such an operation a significant reduction of water content would be obtained as a result of the consumption of water through its reaction with quicklime and of water evaporation caused by the heat released during quicklime hydration.

Optimal dosage of lime to be employed for sludge drying was selected by means of a dedicated trial carried out on a sludge bed of 50 m length, 3 m width and 50 cm thickness which was characterized by an initial water content equal to 22%. On the first half of the section, quicklime was spread over the sludge bed with a dosage of 3% (by weight of the wet sludge), while in the second half the dosage of quicklime was increased to 6%. Sludge-quicklime mixing was thereafter carried out by making use of a pulvimixer. Temperature measured in the sludge bed after treatment was observed to increase significantly and reached values of the order of 40 °C, with a corresponding air temperature of 9 °C. The treated sludge was then left to cool for 1 day and the effectiveness of the considered treatments was thereafter assessed by evaluating water content. Final values of this parameter were equal to 15% and 8% for the 3% and 6% quicklime dosage, respectively. It was therefore concluded that sludge pretreatment with 6% quicklime would be recommended for the remaining field trials. Higher quicklime dosages were not investigated in order to contain processing costs. Although adjustments to the quantity of water added during plant production were still needed even when employing pretreated sludge, they were definitely smaller than those necessary in the first two trials and an improvement of production consistency was clearly observed.

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Although quicklime pretreatment was considered with the only purpose of reducing water content, it was expected that composition and microstructure of sludge would be affected by hydration reactions. Furthermore, it was envisioned that such reactions could also have some effect on the mechanical properties of the SC-CBMs in which the pretreated sludge would be included. In order to address these issues, sludge samples retrieved from the site before and after treatment with quicklime were subjected to X-Ray powder Diffractometry (XRD) tests, performed by making use of a Rigaku model Geigerflex, with the objective of identifying the presence of crystalline phases. Furthermore, the untreated and treated sludge was subjected to observations with a Scanning Electron Microscope (SEM), FEI model Quanta Inspect 200 LV, and to Energy Dispersive X-Ray analyses (EDX), carried out by means of a EDAX Genesis with SUTW detector. Obtained results are displayed in Figure 2 and Figure 3. Results of XRD tests are expressed in the form of spectra which display the intensity (I) measured by the X-ray detector as a function of its position, defined by the angle 2θ. Results of EDX tests, which were performed by targeting specific points of the samples subjected to SEM observations, are given as spectra which show the counts recorded by the detector as a function of their energy level, expressed in kiloelectron volts (keV).

The results of XRD analyses (Figure 2) showed that mixing with quicklime caused a remarkable increase of the peak associated to calcite (identified with code “2”), while the characteristic peaks of other minerals (quartz, dolomite, chlorite and muscovite) remained almost unchanged. Outcomes of the EDX analyses (Figure 3) were consistent with the results of XRD tests, indicating the presence in the treated sludge of hydrated compounds of Ca, Mg, Al and Si, which are similar to those which are formed as products of Portland cement hydration (Jha and Sivapullaiah 2015). Finally, SEM observations (Figure 3) indicated that the mineral sludge initially possessed a morphology characterized by a sheet-like

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arrangement of minerals; after the addition of quicklime, microstructure increased in complexity, with the supplementary presence of amorphous hydrated precipitates.

All SC-CBMs considered in the investigation were produced by making use of Portland cement of the CEM II / A-L 42.5 R type (EN 197-1) and by employing a commercially available polycarboxylate superplasticizer (Advaflow 455, supplied by Grace Products). According to the information obtained from the manufacturers, specific gravity of these two components was equal to 3.150 and 1.060, respectively. For most of the SC-CBMs produced and laid in field trials, the time-dependent hardening of cement paste was tuned by making use of a hardening accelerator (Polarset, supplied by Grace Products). Its specific gravity, as declared by the producer, was equal to 1.250. Water employed for the plant production of the SC-CBMs was drawn from the local supply network and was declared to be exempt from impurities.

2.2 Mixture recipes

Recipes adopted for the production of the SC-CBMs laid in the field trials were defined by following a procedure previously developed by the Authors (Choorackal *et al.* 2019b). Such a procedure entails the definition of a target size distribution of the particles constituting the aggregate skeleton (aggregate fractions, RAP and sludge) and the selection of appropriate dosages of Portland cement, water and function-specific additives (e.g. superplasticizers and hardening accelerators).

The reference size distribution used in the mix design procedure is described by the so-called “modified Andersen and Andreasen equation” proposed by Funk and Dinger (1994) for flowable composites and widely adopted for the mix design of SCCs (Brouwers and Radix 2005a). Such an equation is provided in the following:

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$$P(D) = 100 \cdot \frac{({D_{max}}^q - D^q)}{\left(D_{max}^q - D_{min}^q\right)} \quad (1)$$

where D is the diameter of aggregate particles (in mm), P(D) (expressed in %) is the cumulative percentage passing the sieve with opening equal to D, D_{max} is the maximum diameter of aggregate particles in the mixture (in mm, fixed at 16 for all mixtures and corresponding to P(D) equal to 100%), D_{min} is the minimum diameter of aggregate particles in the mixture (in mm, assumed to be equal to 5 μm for all mixtures), q is the so-called distribution modulus (set equal to 0.21 and 0.23 in the first field trial and thereafter fixed at 0.21 for all the other trials).

The above described reference particle size distribution is shown in Figure 4, where it is compared to the classical maximum density curve defined by the well-known Fuller model (Fuller and Thompson 1907), expressed by the following equation:

$$P(D) = 100 \cdot \left(\frac{D}{D_{max}}\right)^{0.5} \quad (2)$$

It can be observed that the distribution defined by Equation (1), in comparison to the classical Fuller curve, is characterized by a significantly higher content of fines. As proven by past research (Brouwers and Radix 2005b, Uysal and Yilmaz 2011), this is considered necessary for the achievement of the desired flowability of cementitious composites while still guaranteeing an adequate stability of their paste (i.e. limited risks of segregation and bleeding) even in the presence of high water contents.

Percentages of the components constituting the aggregate skeleton of the SC-CBMs were defined by minimizing deviations between their composite particle size distribution and the reference one indicated in Equation (1) and by fixing RAP content at 20% by weight of the sum of all the mineral fractions (aggregates, RAP and sludge). Calculated percentages

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were only marginally affected by variations of the distribution modulus q and were adjusted during the investigation to take into account changes in the composition of employed fractions (see Figure 1). Obtained results are listed in the upper part of Table 2. It can be observed that 42-44% by weight of the aggregate skeleton of the considered SC-CBMs was composed of recycled components (RAP and sludge). Thus, it can be hypothesized that in comparison to mixtures containing only virgin aggregates, the wide-scale production of SC-CBMs may occur with a reduction of costs and environmental impact.

Since it was expected that cement dosage could have a relevant impact on the properties of the mixtures, during the investigation it was varied in a wide range (comprised between 60 kg/m^3 and 200 kg/m^3). In the SC-CBMs which required the use of the hardening accelerator, the dosage of such an additive was set equal to 1.5% by weight of cement as per suggestion of the manufacturer.

Water-to-cement ratio of the mixtures was defined by referring to a surrogate parameter, the water-to-powder ratio (w/p), which is more frequently used in the design of SCC mixtures which contain a relevant quantity of very fine particles (Shi *et al.* 2015). In the case of the SC-CBMs, "powder" is the term which is used to collectively indicate Portland cement and mineral sludge, which jointly contribute to paste fluidity and void filling effects. As proven by the mix design studies previously carried out by the Authors (Choorackal *et al.* 2019b), in order to achieve satisfactory flowability characteristics while guaranteeing an adequate stability, it is recommended to use w/p values of the order of 0.75-0.80. This optimal range was identified by referring to powder pastes containing the same polycarboxylate superplasticizer employed in the research project described in this paper (with a dosage of 0.5% by weight of cement). For the SC-CBMs produced and laid in the field trials, the value of w/p was fixed at 0.80 except for the case of the mixtures with 200 kg/m^3 cement, for which it was reduced to 0.75. The dosage of superplasticizer was in most

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cases fixed at 0.5% by weight of cement although it was increased to 0.75% for the mixtures laid in field trials 3, characterized by cement dosages of 150 kg/m^3 ad 200 kg/m^3.

A summary of the design and composition parameters of all the SC-CBMs considered in the investigation is provided in Table 2, while Table 3 contains the detailed list of all the 14 mixtures which were produced and laid, together with their identification codes which were used in this paper. The code is of the alphanumeric type and in sequence contains the values of distribution modulus (e.g. “0.21”), cement content (e.g. “60”), water-to-powder ratio (e.g. “0.80”) and two additional codes which indicate the presence or absence of the hardening accelerator (NA when not used, YA when used) and the type of sludge employed during mixture production (NP for sludge in its natural state with no pretreatment, YP for sludge preliminarily treated with 6% quicklime).

2.3 Field trials

Field trials entailed the plant-production of several SC-CBMs and the consequent construction of rectangular slabs. Mixing of aggregate fractions, cement, water and additives (if any) was carried out in a cement concrete batching plant, while the addition of RAP and mineral sludge was directly made into the transit mixer which was used to transport the material to the laying site. Transfer of the mixtures into the timber formwork was thereafter performed by means of either a concrete pump (for the first 3 field trials) or a chute (in field trial 4). No compaction or vibration was carried out on after filling the formwork.

In the first three field trials, each slab had a thickness of 60 cm and plan dimensions of either 3 m × 3 m (in the case of trial 1) or 4 m × 3 m (in trials 2 and 3). The slab constructed as part of trial 4 was larger in size, with a height of 1.2 m and plan dimensions equal to 4 m × 14 m. It was constituted in its lower part (1 m thickness) of a SC-CBM containing 100 kg/m^3 of cement, while its upper part was made of a mixture with a cement

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dosage of 60 kg/m^3. The bottom layer was left to cure for a period of 7 days, after which it was overlaid with the second mixture. With respect to the bottom layer, this particular geometry was defined in order to better replicate the thickness of the foundation filling expected in actual road tunnels. The second layer was added on top of it with a reduced thickness (20 cm) in order to gather data on an additional SC-CBM.

Trials 1, 2 and 4 were carried out in the premises of the production plant, while trial 3 was performed inside a road tunnel in order to assess the effect of the curing conditions expected during pavement construction on the in-place characteristics of the mixtures. It should be mentioned that in the case of road tunnels of significant length, curing conditions may be characterized by a very high temperature which can enhance the hardening of cement-bound foundation materials. Field trial 3 included the placement of a set of conduits within the timber formwork which were buried underneath the laid mixtures and were subsequently inspected after allowing vehicles to transit on top of the slabs. In all cases side shuttering of the slabs were removed after one day of curing and before starting field tests. Photographs taken during the construction of the slabs in the four field trials are shown in Figure 5.

2.4 Mixture properties

Field and laboratory tests carried out on the SC-CBMs employed in the various field trials focused on properties which were considered relevant for the evaluation of their suitability in road tunnel pavement foundations. Field tests assessed the flowability and void content of the mixtures in their fresh state and the bearing capacity of constructed slabs. Laboratory tests, which were carried out on specimens casted on site, provided information on the mechanical properties of the mixtures in the hardened state as a function of curing time.

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Flowability was considered as a key property to be checked since it vital for the creation of a homogeneous pavement foundation in tunnels even in the presence of buried conduits. Furthermore, it is essential in order to allow a mixture to be easily pumped for long distances during construction operations with no occurrence of bleeding or segregation phenomena. Determination of void content was also considered relevant in the context of the research project since such a parameter provides a measure of the actual packing reached by the cement-bound composite, in which settlements in time should be prevented in order to guarantee a stable behavior as a pavement foundation.

Flowability was determined as per ASTM D6103, which requires the measurement of the spread diameter (D_s) obtained by allowing a sample to flow under its own weight after being released from a standard cylinder (75 mm in diameter and 150 mm in height). At the time of diameter measurement, visual observations are also carried out in order to detect the occurrence of any bleeding or segregation phenomena. Air content (A_s) was assessed as per ASTM C231 (pressure method), which requires samples to be subjected to the action of air pressure in a sealed vessel.

Bearing capacity of the constructed slabs was assessed by performing static plate loading tests on their surface after 1, 3, 7 and 28 days of curing, as per German standard DIN 18134. The test procedure involves the application of vertical loads to a circular plate with 300 mm diameter following a predefined sequence which includes two loading phases with an intermediate unloading. Based on the recorded values of applied vertical stress and measured vertical settlements, the so-called strain modulus E_v (indicated as E_{v1} or E_{v2} when associated to the first or second loading cycle, respectively) is calculated by means of the following expression:

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$$E_v = 1.5 \cdot r \cdot \frac{1}{a_1 + a_2 \cdot \sigma_{0max}} \tag{3}$$

where r is the radius of the loading plate (in mm), σ_{0max} is the maximum applied stress (in MPa, usually equal to 0.50 MPa but reduced to lower values when vertical settlement reaches the maximum allowable limit of 5 mm), a_1 and a_2 are fitting constants which derive from the modelling of the stress-settlement data according to the following equation:

$$s = a_0 + a_1 \cdot \sigma_0 + a_2 \cdot {\sigma_0}^2 \tag{4}$$

where s is the measured vertical settlement (in mm), σ_0 is the applied stress (in MPa), a_0 is a fitting constant.

Results obtained from plate loading tests are usually employed as part of quality assurance procedures for the assessment of the bearing capacity and of the state of compaction of earthworks. Typical acceptance criteria which are adopted in practice establish that E_{v2} should be greater than 45 MPa or 120 MPa for tests carried out on the surface of soil embankments (or subgrade) and on the top of the overlying granular capping layer, respectively (ZTVE-StB 1994). Furthermore, it is usually required that the ratio E_{v2}/E_{v1} be less than 2.5 in order to guarantee the achievement of satisfactory compaction levels. As an alternative, minimum threshold limits may also be fixed for E_{v1}, which is often expected to be greater than 20 MPa for soil embankments.

During the investigation carried out on the SC-CBMs laid in the field trials, results obtained from plate loading tests were analyzed by mainly focusing on E_{v1} in the early phases of curing (up to 7 days) and on E_{v2} in fully cured conditions (after 28 days). In fact, E_{v1} was related to the ability of the mixtures to resist to the action of construction traffic, while E_{v2} was considered as an indicator of the bearing capacity guaranteed during the service life of

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the pavement. Assessment of the E_{v2}/E_{v1} parameter was not considered to be of any interest since the SC-CBMs are self-compacting by definition.

Supplementary information on the potential resistance of newly-laid SC-CBMs to the loading of construction equipment was obtained by means of a further test, which involved subjecting the constructed slabs to the slow passage of a 40 tons truck in the early phase of hardening (after either 1 or 3 days of curing). Loads were applied by means of a front single axle with single wheels and a rear tandem axle with dual wheels, while tire inflation pressure was fixed at 0.55 MPa. After the transit of the vehicle, the surface of the slabs was inspected for the identification of induced permanent deformations or damage, if any.

Mixtures in the hardened state were subjected to testing in the laboratory for the measurement of compressive strength and resilient modulus at given curing times. Compressive strength of the mixtures was evaluated after 1, 3, 7 and 28 days of curing by making use of standard 150 mm cubes as per EN 12390-2/3. Results obtained in the early stages of curing (up to 7 days) were analysed in combination with the outcomes of the traffic simulation tests described above in order to gain information on the resistance of the SC-CBMs to the action of construction equipment. Results obtained in full curing conditions (after 28 days) were considered with the purpose of evaluating the excavatability of the mixtures.

Resilient modulus (M_r) of the SC-CBMs was determined after 28 days of curing by means of tests carried out in a triaxial cell as per AASHTO T 307-99 (sub-base protocol). These tests were considered fundamental within the research project since they yield data which can be employed as part of pavement structural analyses. Although they are more commonly employed for the characterization of subgrade soils and granular sub-bases, they have also been used for the evaluation of different types of materials which include cement-stabilized and cold-recycled mixtures (Taha *et al.* 2002, Santagata *et al.* 2010, Fatemi and

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Imaninasab 2016). Test specimens were prepared by filling cylindrical moulds 100 mm in diameter and 200 mm in height. As per its definition, resilient modulus was calculated in the various stress conditions imposed during the test (obtained by changing both confining pressure and deviatoric stress) by making use of the following equation:

$$M_r = \frac{\sigma_d}{\varepsilon_r} \tag{5}$$

where σ_d is the repeated deviatoric stress applied along the vertical direction and ε_r is the corresponding recoverable portion of vertical axial strain.

3. Results and discussion

3.1 Field tests on fresh mixtures

Results of flowability and air content tests obtained on SC-CBMs produced and laid in the field trials are shown in Table 4, which also contains the values of parameter Vp/Vg, defined as the ratio between the volume of the components constituting the cement-sludge-water paste (V_p) and the volume of the granular fraction constituted by virgin aggregates and RAP (V_g). As indicated in a previous study (Riviera *et al.* 2019), such a parameter can be meaningful in the assessment of flow properties of cement-bound mixtures. In those cases in which V_p/V_g is too low, it can be associated to mixtures in which the coarse fraction is not lubricated enough by the paste; on the contrary, when V_p/V_g is too high, it can correspond to mixtures in which phase separation can occur in the form of bleeding or segregation.

It can be observed that all considered SC-CBMs exhibited a very low air content which was contained within a narrow range (1.4-2.5%). Such an outcome is consistent with the composition of the mixtures, which were designed as self-levelling composites with an excellent particle packing and very high percentage of fines. Furthermore, they were all

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characterized by similar values of the water-to-powder ratio (w/p), equal to 0.75 or 0.80, which dictates the consistency of the cement-sludge-water paste in the fresh state.

The effectiveness of the approach adopted for the formulation of the SC-CBMs was confirmed by the results of the flowability tests, which in all cases yielded values of the spread diameter (D_s) greater than 200 mm. In such a context it should be mentioned that CLSMs for trench filling operations are usually required to exhibit a D_s greater that 170 mm, while it is recommended that it should be less than 250 mm in order to reduce the risk of segregation or bleeding (Folliard *et al.* 2008). In the case of the considered SC-CBMs it should be underlined that these undesired phenomena did not occur even in those cases in which D_s was greater than 300 mm (i.e. for 5 mixtures out of 14). This is due to the soundness of the adopted mix design approach, which guaranteed an acceptable balance between the cement-sludge-water paste and the granular skeleton of the mixture.

Since the considered mixtures presented an almost constant w/p value, variations of D_s as a function of the changes in mixture composition were assessed by referring to the effects of other controlling factors. It was observed that in general terms D_s tended to increase with the increase of cement content (or, equivalently, of V_p/V_g). However, it was noticed that flowability was also affected by the presence of the accelerating additive, the presence of which caused an increase of D_s for each given cement content, probably as a result of an additional lubricating action. Furthermore, when comparing the flowability of mixtures characterized by the same cement dosage, regardless of the presence or absence of the accelerating agent, it was observed that quicklime pretreatment of the sludge led to a reduction of D_s. This can be explained by referring to the hydration precipitates highlighted by means of the SEM analyses described in section 2.1, which may have the effect of increasing the internal friction of the mineral powder contained in the mixtures.

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The outcomes illustrated above can be clearly recognized by plotting the data of Table 4 as shown in Figure 6, where D_s is displayed as a function of cement content. In such a plot available data have been grouped into four different series corresponding to the absence or presence of the hardening accelerator (codes NA or YA) and of the quicklime pretreatment (codes NP or YP). In the case of the mixtures which differed only in terms of their distribution modulus (equal to 0.21 or to 0.23), average values have been considered. For those mixtures which exhibited D_s values greater than 350 mm, such a value was considered in the plots.

By analyzing Figure 6, it is interesting to note that the combined effects of the use of the accelerator and of quicklime pretreatment evened out, leading to D_s values which up to a cement dosage of 150 kg/m^3 were almost identical to those of the mixtures prepared with no accelerator and with untreated sludge. The consistency of experimental data with the interpretation provided above is remarkable, especially if it is considered that flowability tests are quite empirical and are characterized by an inherent non-negligible variability.

3.2 Laboratory tests on hardened mixtures

3.2.1 Compressive strength

Results of compressive strength tests carried out on the SC-CBMs are given in Table 5. As expected, in all cases compressive strength progressively increased with curing time. However, since the composition of the considered mixtures varied considerably, obtained values were dispersed in very broad ranges (equal to 0.10-2.51 MPa after 1 day of curing, 0.19-4.60 MPa after 3 days of curing, 0.23-5.65 MPa after 7 days of curing, 0.28-7.38 MPa after 28 days of curing).

Although the SC-CBMs considered in the investigation were different from CLSMs in terms of their composition, they were expected to possess similar properties in terms of

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strength. Thus, for the critical analysis of obtained results, reference was made to the requirements provided in literature for CLSMs, which are expressed in the form of maximum allowable values of compressive strength after 28 days of curing. According to the guidelines proposed by ACI (2013), such a limiting value can be set at 8.3 MPa for all CLSMs, whereas various authors have recommended a maximum limit of 2.1 MPa for those applications in which the CLSMs are required to be easily excavatable (Pierce *et al.* 2003, Trejo *et al.* 2004). While the first requirement was met by all mixtures laid in the field trials, the second one was satisfied only when the cement dosage was equal to 60 kg/m^3 or 100 kg/m^3. With respect to short-term compressive strength (corresponding to curing times of up to 7 days), minimum required values are not specified for CLSMs since they are usually employed for filling applications with no structural function. Thus, as discussed in detail in section 3.3, short-term acceptance thresholds for the self-compacting mixtures subjected to investigation originated from the results obtained from bearing capacity field tests.

Experimental results listed in Table 5 are plotted as a function of curing time in Figure 7 (lower cement dosages) and Figure 8 (higher cement dosages), grouping available data into the same four series defined for the analysis of flowability results (Figure 6).

The mixtures which were produced during the first field trial (and two further mixtures prepared for field trial 2) contained mineral sludge which had not been subjected to any pretreatment and did not benefit from the use of any hardening accelerator. For these mixtures, indicated with code NA-NP, it was found that after 28 day of curing, achieved strength was extremely low in the case of low cement dosages (60 kg/m^3 and 100 kg/m^3), while it exceeded the 2.1 MPa excavatability limit for higher cement dosages (150 kg/m^3 and 200 kg/m^3). Furthermore, in the short term all these mixtures exhibited a relatively low strength (less than 0.40 MPa after 1 day of curing, less than 2.0 MPa after 3 days) and a very low rate of strength development (from production up to 7 days of curing). In absolute terms

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these outcomes could not be evaluated with respect to the need of the corresponding foundations to be adequately resistant to construction traffic in the early phases of curing. As previously mentioned, such an analysis required the combined evaluation of the results obtained from full-scale load simulation tests (see section 3.3).

In order to modify the strength characteristics of the initially laid mixtures, use was made of the previously mentioned accelerating additive. Experimental data that could be directly compared to those illustrated above were obtained in field trial 2, in which SC-CBMs containing the hardening accelerator were produced with 100 kg/m^3 and 150 kg/m^3. Obtained results (corresponding to the YA-NP series in Figure 7 and in Figure 8) showed that the employed additive had very limited effects on the strength characteristics of the mixtures. In particular, variations with respect to the initially produced SC-CBMs were negligible at all curing times. It should be mentioned that unfortunately, as a result of constraints in logistics, the cubical specimens casted on site were stored overnight in the field and were consequently exposed to subzero temperatures before being transported to the laboratory. Thus, it was postulated that such an occurrence may have negatively influenced the effectiveness of the accelerating additive thereby hindering strength development (Kim *et al.* 1998).

As illustrated in section 2.1, starting from trial 3, the sludge employed for the production of the SC-CBMs was pretreated with quicklime in order to achieve a better control of mixture water content. Experimental results indicated that, as in the case of flowability (see section 3.1), compressive strength was significantly affected by sludge pretreatment. This can be appreciated by considering the data of the NA-YP and YA-YP series plotted in Figure 7 and Figure 8, which indicate that sludge pretreatment led to a significant increase of compressive strength for all cement dosages and at all curing times.

When comparing the NA-YP and YA-YP series, it was confirmed that the hardening accelerator has a limited effect on strength values, with absolute changes that in most cases

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were smaller that 0.2 MPa. It can be noticed that after 28 days of curing the mixtures containing pretreated sludge achieved strength values which were acceptable from the viewpoint of exacavatability (i.e. smaller than 2.1 MPa) only for low cement dosages (60 kg/m^3 and 100 kg/m^3). Furthermore, these mixtures exhibited short-term strength values (after 1, 3 and 7 days of curing) which were definitely higher than those found for the corresponding mixtures containing untreated sludge.

3.2.2 Resilient modulus

Results obtained from resilient modulus tests carried out after 28 days of curing on the various SC-CBMs are provided in Table 6, where they are expressed in terms of the minimum and maximum values achieved in the investigated range of stress conditions. These are indicated in terms of the first stress invariant (θ), also known as bulk stress, which during the tests varied between 0.08 MPa and 0.66 MPa. Experimental results are also displayed in Figure 9 (lower cement dosages) and Figure 10 (higher cement dosages), where the logarithm of resilient modulus (M_r, expressed in MPa) is plotted as a function of the logarithm of θ (also expressed in MPa). Data have been grouped into the same 4 series utilized for the discussion of flowability and compressive strength results (see Figures 6-8).

As expected, resilient modulus was extremely sensitive to variations of cement dosage, with progressively higher values recorded in all stress conditions when passing from 60 kg/m^3 to 200 kg/m^3. By considering increasing cement dosage (60, 100, 150 and 200 kg/m^3), recorded variation ranges were equal to 99-474 MPa, 107-778 MPa, 304-710 MPa and 386-874 MPa. As indicated in Figure 9 and Figure 10, all mixtures exhibited a non-negligible non-linearity which was observed to be of the stress-hardening type. Such a sensitivity, which can be appreciated by considering the slope of the regression lines fitted to the experimental data points, in general terms was found to decrease with the increase of

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cement dosage. Such an observation is in line with previous findings (Puppala *et al.* 2011b, Mohammadinia *et al.* 2016) and is due to the fact that as the volume of hardened paste increases in a granular composite, its highly linear response has a greater effect on the overall mechanical response, thereby reducing non-linearity.

Acceptance limits for the resilient modulus cannot be defined in absolute terms since stiffness requirements for pavement foundations should be identified as a function of pavement cross section, environmental conditions and design traffic (Riviera *et al.* 2020). However, it was encouraging to observed that values recorded during the investigation were comparable to those of high-quality sub-base materials (Dawson *et al*. 2000, Nataatmadja and Tan 2001, Kumar *et al.* 2006). As in the case of compressive strength (see section 3.2), it was found that use of the hardening accelerator and of sludge pretreatment led to an increase of M_r. However, recorded effects were more evident for mixtures prepared with lower cement dosages (60 kg/m^3 and 100 kg/m^3).

In order to capture in more detail the influence on M_r of the various compositional variables, experimental data were fitted to the following model proposed by Puppala *et al.* (2011a):

$$M_r = k_1 \cdot p_a \cdot \left(\frac{\sigma_3}{p_a}\right)^{k_2} \cdot \left(\frac{\sigma_d}{p_a}\right)^{k_3} \quad (6)$$

where p_a is atmospheric pressure (equal to 0.10133 MPa), σ_3 is confining stress (in MPa), σ_d is deviatoric stress (in MPa), k_1, k_2 and k_3 are material-dependent constants.

Results obtained from model fitting are shown in Table 7, which contains the values of the material-dependent constants and associated coefficients of determination (R^2).

By analysing the data provided in Table 7, it was confirmed that the model given in Equation (6) is suitable for the description of the resilient response of cement-bound mixtures, with R^2 values which in most cases were greater than 0.97. Few exceptions were

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found when considering mixtures containing untreated sludge (with cement dosages equal to 60 kg/m^3 and 150 kg/m^3).

The limiting values of the resilient modulus, expressed by parameter k_1, varied as previously indicated, increasing with cement dosage and revealing the stiffening influence of the hardening accelerator and of sludge pretreatment. Due to the presence of the hardened cement paste, most of the mixtures exhibited a response under loading which was only marginally affected by shear stresses, thereby showing a low susceptibility to variations of the deviatoric stress σ_d. This led to low values of parameter k_3, which for the majority of the tested SC-CBMs varied in a very narrow range (comprised between 0.06 and 0.14). The only exceptions came from two of the mixtures produced with untreated sludge and with the lowest cement dosages, equal to 60 kg/m^3 and 100 kg/m^3, which yielded k_3 values respectively equal to 0.34 and 0.55. Such an outcome is consistent with expectations since these mixtures were those with the lowest overall stiffness and were possibly characterized by a less efficient bonding of the cement paste. When considering all the SC-CBMs subjected to testing, greater variations were observed for parameter k_2, which varied between 0.15 and 0.31. This indicates that the mixtures were more sensitive to variations of confining pressure σ_3 which, as extensively shown in literature, can cause non-negligible volumetric effects (Arulrajah *et al.* 2012). No specific relationships could be identified between mixture composition and parameter k_2.

3.3 Field tests on constructed slabs

Results of plate loading tests performed on the slabs constructed during field trials are given in Table 8, where they are expressed in terms of the strain moduli E_{v1} and E_{v2} measured at the first and second loading cycle, respectively. For the SC-CBMs laid in field trials 1 and 2, tests after 1 day of curing were not carried out. In the first case this was due to the fact that

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the slabs did not seem to be hardened enough and that on their surface there was still an excess of water. In the second case, there were concerns on the effectiveness of curing since the slabs were exposed overnight to subzero temperatures. Slabs constructed as part of trial 3 were subjected to testing only after 1 day of curing since there were constraints in terms of logistics to carry out further tests in the tunnel. Plate loading tests on the SC-CBMs laid in field trial 4 were discontinued after 7 days of curing due to the fact that they were thereafter overlaid with asphalt layers for the construction of a full pavement cross section (Riviera *et al.* 2020).

Early curing traffic simulation tests were carried out with a heavy vehicle as described in section 2.4 on the same day of the earliest plate loading test (see Table 8), with the only exception of the mixtures laid in field trial 4, which were not subjected to such tests because of safety concerns related to the high elevation of the slab surface. In all cases obtained results were positive, the fully loaded truck being capable of slowly moving on top of the slabs with no true damage to the laid SC-CBMs. In the case of the mixtures characterized by lower cement dosages (60 kg/m^3 and 100 kg/m^3), the truck created visible surface imprints which had a depth approximately corresponding to tire tread; for the mixtures with a higher cement dosage (150 kg/m^3 and 200 kg/m^3), the surface remained perfectly smooth even after loading.

When considering the results obtained from the first loading cycle applied during plate loading tests, several observations were made. As discussed in the following, they are related to the shape of the stress-settlement curves and to the nature of recorded displacements. In the case of the 4 mixtures laid in field trial 1, which were characterized by relatively low values of compressive strength (see section 3.2.1) and resilient modulus (see section 3.2.2), significant settlements occurred after 3 and 7 days of curing under the first loading increment (up to 0.01 MPa). As shown in Figure 11, such an anomaly ceased to occur

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when reaching 28 days of curing. These outcomes can be explained by hypothesizing that in the very early phase of curing these mixtures exhibited an initial settlement due to the excess of water at the slab surface. Additional effects may be due to the slow hardening of the slabs, which is consistent with the very low rate of strength development highlighted when discussing compressive strength results.

In general terms it was noticed that the stress-settlement curves obtained from experimental measurements were of three possible types. In the case of the SC-CBMs laid in field trial 1, characterized by a low cement dosage (60 kg/m^3 and 100 kg/m^3) with no hardening accelerator and containing untreated sludge, the stress-settlement relationships were found to be non-linear with a clear stress-softening character. For the mixtures with higher cement contents (150 kg/m^3 and 200 kg/m^3) produced for field trial 2, with and without hardening accelerator, recorded curves were clearly linear in the early stage of curing (i.e. up to 7 days), while at longer curing time (after 28 days) there were characterized by a non-negligible stress-stiffening. Results of plate loading tests carried out on the slabs of field trial 3, which were prepared with SC-CBMs characterized by high cement dosages (150 kg/m^3 and 200 kg/m^3), yielded stress-settlement curves of the stress-stiffening type even after 1 day of curing. However, it should be considered that the mixtures contained sludge pretreated with quicklime and that the slabs were cured inside a tunnel at a relatively high temperature (of the order of 25°C). It is very interesting to note that the mixture with a cement dosage of 100 kg/m^3 laid in field trial 4 exhibited the three types of responses as a function of curing time, changing from stress-softening (after 1 day of curing) to linear (after 3 days of curing) and then to stress-stiffening (after 7 days of curing). In such a context it should be underlined that hardening progression benefited from the presence of both the accelerating additive and of the quicklime pretreatment. Figure 12 shows examples of the three types of stress-settlement curves recorded during the investigation.

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For a more detailed discussion of experimental results, analysis of the stress-settlement curves obtained from the first loading cycle in plate loading tests was supplemented by the evaluation of the nature of recorded displacements, which can combine reversible and permanent components (Mamatha and Dinesh 2018). Such an assessment was carried out by considering the response obtained during unloading and in particular by comparing the residual settlement after complete stress removal ($s_{0,u}$) to the maximum value recorded under the maximum applied stress ($s_{max,1}$). In quantitative terms, this was done by calculating the percentage of permanent settlement (s_p), defined as indicated in the following expression:

$$s_p = \frac{s_{0,u}}{s_{max,1}} \cdot 100 \qquad (7)$$

Values of the s_p parameter are listed in Table 9 for all slabs subjected to testing.

The data listed in Table 9 clearly indicate that permanent deformations occurring under the first loading cycle of plate loading tests was significant at all curing times for the mixtures considered in the investigation. In general terms it was observed that these non-reversible settlement components decreased in time with the progress of hardening and were affected by cement dosage, use of the hardening accelerator and sludge pretreatment. These factors had the same type of effects which were observed for compressive strength and resilient modulus test results (see section 3.2).

It should be underlined that permanent settlements occurring in the foundation as a result of the first loading cycle imposed during plate loading tests are not representative of those which are expected in service under the action of regular traffic. This is due to the fact that in all cases the foundation is bound to be subjected to loading of construction equipment during the laying and compaction of the upper layers of the pavement. Thus, most of the permanent settlements are expected to take place in such phases. Furthermore, it should also

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be considered that in service the pressure applied to the top of the foundation is significantly reduced by the load distribution effect due to the upper pavement layers, with a consequent further reduction of potential permanent settlements.

As mentioned in the previous sections, measurement of strain modulus E_{v1} was considered of interest for the assessment of the possibility of subjecting the SC-CBMs to the action of construction traffic in the early phases of curing without any damage. In such a context, the identification of a minimum threshold value to be adopted as an acceptance criterion stemmed from the combined analysis of recorded E_{v1} values and of the outcomes of the simulation tests carried out by means of the fully loaded truck. Thus, by considering obtained results, it can be stated that trafficability conditions were reached by the constructed slabs when achieving a E_{v1} value not smaller than 10 MPa. Such a limit was barely met by the slab prepared in field trial 1 with a cement dosage of 60 kg/m^3 and with a distribution modulus of 0.23. Nevertheless, even in this case after the passage of the heavy vehicle no significant damage occurred in the constructed slabs.

It can be noticed that trafficability conditions were reached at curing times which correspond to compressive strength values not smaller than 0.19 MPa (see Table 5). For the specific type of SC-CBMs considered in the investigation, such a value can therefore be used as an acceptance limit which when satisfied identifies the curing time needed before allowing construction traffic to move on top of the pavement foundation.

In the context of the investigation, evaluation of strain modulus E_{v2} was carried out with the main purpose of identifying the bearing capacity of the pavement foundation in service (Choi *et al.* 2018) Consequently, analysis of obtained results mainly focused on data obtained in fully cured conditions, which were hypothesized to be reached 28 days after placement. As indicated in Table 8, these tests were carried out only on the slabs constructed as part of field trials 1 and 2. Obtained results showed that for lower cement dosages (60

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kg/m^3 and 100 kg/m^3) E_{v2} was of the order of 200-400 MPa, whereas it reached significantly higher values, greater than 1,000 MPa, in the case of higher cement dosages (150 kg/m^3 and 200 kg/m^3). It was also observed that the evolution of E_{v2} as a function of curing time was highly dependent upon mixture composition, but no clear trends could be identified. For those mixtures which were subjected to testing at curing times less than 28 days, recorded values were of the same order of magnitude of those of the other mixtures.

The data listed in Table 8 indicate that recorded E_{v2} values were significantly higher than the classical threshold limit adopted for embankments covered by a capping layer, equal to 120 MPa. Thus, from a quality assurance viewpoint, all SC-CBMs are fit for purpose in terms of their long-term bearing capacity.

3.4 Recommended acceptance criteria

Results collected during the experimental investigation and discussed in the previous sections can be used for the identification of performance-related acceptance criteria, outlined in the following, which may be adopted in future construction works in road tunnels.

Flowability, which may be considered as a prerequisite for the acceptance of any SC-CBM, should be continuously checked during production and at the laying site. In such a context, it seems appropriate to assume a minimum allowable value of the spread diameter equal to 200 mm.

In order to ensure that the SC-CBMs laid for the formation of the pavement foundation can be subjected to the loading of construction equipment in the early phases of curing with no significant damage, it is recommended to refer to two different acceptance thresholds. When considering the properties of the mixture, either in the design phase or during quality assurance operations, the curing time needed to reach a value of compressive strength equal to 0.19 MPa (determined as per EN 12390-2/3) needs to be evaluated. As

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discussed in the paper, such a curing time can be considered as the minimum time which is needed before allowing the foundation to be subjected to heavy loads. As a supplement to such an evaluation, plate loading tests can be carried out in the field in accordance to DIN 18134. It is suggested that construction equipment should be allowed to transit on the foundation only after recording a value of the strain modulus E_{v1} greater than 10 MPa. This limiting value may be prudentially increased to 20 MPa, which is sometimes used for the quality assurance of standard earthworks, in order to account for variability of SC-CBM production. For the SC-CBMs laid in the field trials were characterized by a low cement dosage (60 kg/m^3 and 100 kg/m^3), it was observed that trafficability conditions were always reached after 3 days of curing.

Other acceptance criteria which may be considered in construction works include the verification of the long-term stiffness and bearing capacity of the foundation. These properties may be assessed after the achievement of full curing (i.e. after 28 days) by performing resilient modulus tests (in the laboratory, as per AASHTO T 307) and plate loading tests (in the field). Resilient modulus values should be employed as part of pavement design analyses, whereas the strain modulus E_{v2} derived from plate loading tests may be compared to the classical 120 MPa threshold assumed for general road construction activities. Too high values of the resilient and strain moduli may be suspect in terms of the potential brittleness of the materials, with the consequent risk of undesired reflective cracking phenomena in the completed pavement.

It is anticipated that the acceptance criteria illustrated above may need to be adjusted and fine-tuned when considering the results coming from a broader range of SC-CBMs. Nevertheless, they can be regarded as a useful reference for future applications.

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4. Conclusions

The research work presented in this paper focused on self-compacting cement-bound mixtures (SC-CBMs) intended for use in pavement foundations in road tunnels. These mixtures possess a peculiar composition since they contain a high percentage of fines, a significant quantity of recycled materials (RAP and mineral sludge), and two function-specific additives (a superplasticizer and a hardening accelerator).

Based on the results obtained during the experimental investigation, which entailed full-scale field trials with the production and laying of 14 different SC-CBMs, it can be concluded that the considered mixtures are suitable for their intended use. In particular, it was found that SC-CBMs prepared with a cement dosage of up to 100 kg/m^3 possess the required properties of flowability, strength and stiffness. On the contrary, mixtures with higher cement dosages (150 kg/m^3 and 200 kg/m^3) fail to meet all the performance-related requirements as a result of their high long-term strength which jeopardizes excavatability. Furthermore, they may be more prone to long-term cracking and may consequently promote the occurrence of reflection cracks in the overlying pavement layers.

It was confirmed that the adopted mix design procedure, based on the use of a reference particle size distribution and on the optimization of the composition of cement paste, leads to SC-CBMs which are characterized by an adequate flowability, with a spread diameter (determined as per ASTM D6103) greater than 200 mm, and by a satisfactory stability, with no occurrence of bleeding or segregation. The short-term and long-term mechanical properties of the SC-CBMs can then be tuned by selecting the appropriate cement dosage and by considering the additional effects which are due to other components. In the investigation described in this paper it was found that the hardening accelerator had only limited effects, whereas a significant increase of strength and stiffness was observed when employing mineral sludge pretreated with quicklime.

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Results collected during the experimental investigation were used for the identification of recommended performance-related acceptance criteria which may be adopted in future construction works in road tunnels and possibly improved when considering the results coming from a broader range of SC-CBMs.

Further studies are needed in order to address several issues which were not considered in the investigation described in this paper. These include the assessment of long-term permanent deformations and cracking phenomena under repeated loading and the evaluation of life-cycle costs. Furthermore, additional investigations involving the use of other recycled components (e.g. construction and demolition waste and industrial by-products) are strongly encouraged.

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Table 1. Specific gravity of aggregate fractions, RAP and mineral sludge.

Fraction	SG	
	First sampling	Second sampling
Sand 0-8	2.745	2.786
Gravel 8-18	2.744	2.716
RAP	2.530	2.485
Sludge	2.786	2.810

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Table 2. Design and composition parameters of SC-CBMs laid in field trials.

	Trial 1		Trial 2	Trial 3	Trial 4
Distribution modulus, q	0.21	0.23	0.21	0.21	0.21
Coarse sand 0-8 (%)	39	40	36	36	36
Gravel 8-18 (%)	17	18	20	20	20
RAP (%)	20	20	20	20	20
Sludge (%)	24	22	24	24	24
Cement (kg/m^3)	60 - 100	60 - 100	100 - 150 - 200	150 - 200	60 - 100
Water-to-powder ratio, w/p	0.80	0.80	0.80 - 0.75	0.80 - 0.75	0.80
Accelerator (% by weight of cement)	-	-	1.5	1.5	1.5
Superplasticizer (% by weight of cement)	0.5	0.5	0.5	0.75	0.5

Table 3. SC-CBMs laid in field trials.

Trial	q	Cement content (kg/m^3)	w/p	Accelerator	Pre-treatment of sludge	Identification code
1	0.21	60	0.8	No	No	0.21-60-0.80-NA-NP
	0.23	60	0.8	No	No	0.23-60-0.80-NA-NP
	0.21	100	0.8	No	No	0.21-100-0.80-NA-NP
	0.23	100	0.8	No	No	0.23-100-0.80-NA-NP
2	0.21	100	0.8	Yes	No	0.21-100-0.80-YA-NP
	0.21	150	0.8	Yes	No	0.21-150-0.80-YA-NP
	0.21	150	0.8	No	No	0.21-150-0.80-NA-NP
	0.21	200	0.75	No	No	0.21-200-0.80-NA-NP
3	0.21	150	0.8	No	Yes	0.21-150-0.80-NA-YP
	0.21	150	0.8	Yes	Yes	0.21-150-0.80-YA-YP
	0.21	200	0.75	No	Yes	0.21-200-0.75-NA-YP
	0.21	200	0.75	Yes	Yes	0.21-200-0.75-YA-YP
4	0.21	100	0.8	Yes	Yes	0.21-100-0.80-YA-YP
	0.21	60	0.8	Yes	Yes	0.21-60-0.80-YA-YP

Table 4. Flowability and air content of SC-CBMs laid in field trials.

	Identification code	D_s (mm)	A_s (%)	V_p/V_g
Trial 1	0.21-60-0.80-NA-NP	210	2.0	1.13
	0.23-60-0.80-NA-NP	220	2.1	1.02
	0.21-100-0.80-NA-NP	280	2.0	1.24
	0.23-100-0.80-NA-NP	300	2.0	1.12
Trial 2	0.21-100-0.80-YA-NP	> 350	1.7	1.24
	0.21-150-0.80-YA-NP	340	1.4	1.39
	0.21-150-0.80-NA-NP	310	1.4	1.38
	0.21-200-0.80-NA-NP	300	2.0	1.47
Trial 3	0.21-150-0.80-NA-YP	250	2.5	1.38
	0.21-150-0.80-YA-YP	310	2.5	1.39
	0.21-200-0.75-NA-YP	280	1.5	1.47
	0.21-200-0.75-YA-YP	> 350	1.5	1.48
Trial 4	0.21-100-0.80-YA-YP	290	1.8	1.24
	0.21-60-0.80-YA-YP	220	1.9	1.13

Table 5. Compressive strength of SC-CBMs laid in field trials.

	Identification code	Compressive strength (MPa)			
		1 day	3 day	7 day	28 days
Trial 1	0.21-60-0.80-NA-NP	0.12	0.19	0.23	0.28
	0.23-60-0.80-NA-NP	0.11	0.25	0.26	0.28
	0.21-100-0.80-NA-NP	0.23	0.40	0.53	0.67
	0.23-100-0.80-NA-NP	0.10	0.19	0.27	0.34
Trial 2	0.21-100-0.80-YA-NP	0.15	0.23	0.46	0.58
	0.21-150-0.80-YA-NP	0.35	0.98	1.98	2.47
	0.21-150-0.80-NA-NP	0.32	0.99	1.93	2.16
	0.21-200-0.80-NA-NP	0.39	1.80	3.00	3.77
Trial 3	0.21-150-0.80-NA-YP	1.17	2.27	2.52	3.66
	0.21-150-0.80-YA-YP	1.13	2.26	2.71	3.72
	0.21-200-0.75-NA-YP	2.51	4.05	5.41	6.92
	0.21-200-0.75-YA-YP	2.43	4.60	5.65	7.38
Trial 4	0.21-100-0.80-YA-YP	0.31	0.84	1.26	1.67
	0.21-60-0.80-YA-YP	0.43	0.54	0.79	0.90

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Table 6. Resilient modulus of SC-CBMs laid in field trials.

	Identification code	Mr (MPa)	
		Minimum	Maximum
Trial 1	0.21-60-0.80-NA-NP	99	302
	0.23-60-0.80-NA-NP	119	303
	0.21-100-0.80-NA-NP	115	584
	0.23-100-0.80-NA-NP	107	454
Trial 2	0.21-100-0.80-YA-NP	250	504
	0.21-150-0.80-YA-NP	304	601
	0.21-150-0.80-NA-NP	310	559
	0.21-200-0.80-NA-NP	403	658
Trial 3	0.21-150-0.80-NA-YP	365	710
	0.21-150-0.80-YA-YP	358	681
	0.21-200-0.75-NA-YP	420	819
	0.21-200-0.75-YA-YP	386	874
Trial 4	0.21-100-0.80-YA-YP	352	778
	0.21-60-0.80-YA-YP	178	474

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Table 7. Fitting parameters derived from resilient modulus modelling of SC-CBMs laid in field trials.

	Identification code	k_1	k_2	k_3	R^2
Trial 1	0.21-60-0.80-NA-NP	2262	0.13	0.38	0.830
	0.23-60-0.80-NA-NP	2374	0.17	0.30	0.899
	0.21-100-0.80-NA-NP	3308	0.22	0.64	0.968
	0.23-100-0.80-NA-NP	3019	0.25	0.47	0.965
Trial 2	0.21-100-0.80-YA-NP	4298	0.27	0.08	0.992
	0.21-150-0.80-YA-NP	5021	0.29	0.06	0.983
	0.21-150-0.80-NA-NP	4570	0.22	0.08	0.972
	0.21-200-0.80-NA-NP	5702	0.17	0.08	0.976
Trial 3	0.21-150-0.80-NA-YP	5943	0.27	0.06	0.983
	0.21-150-0.80-YA-YP	5458	0.22	0.11	0.975
	0.21-200-0.75-NA-YP	6809	0.23	0.09	0.989
	0.21-200-0.75-YA-YP	6981	0.24	0.14	0.998
Trial 4	0.21-100-0.80-YA-YP	6289	0.29	0.11	0.994
	0.21-60-0.80-YA-YP	3889	0.31	0.12	0.989

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Table 8. Strain moduli of SC-CBMs laid in field trials.

	Identification code	E_{v1} (MPa)				E_{v2} (MPa)			
		1 day	3 days	7 days	28 days	1 day	3 days	7 days	28 days
Trial 1	0.21-60-0.80-NA-NP	-	15.2	27.5	30.8	-	74.5	237.4	258.1
	0.23-60-0.80-NA-NP	-	11.0	16.5	28.8	-	330.4	168.7	414.3
	0.21-100-0.80-NA-NP	-	20.3	44.9	47.5	-	251.9	384.8	216.9
	0.23-100-0.80-NA-NP	-	17.6	55.2	57.7	-	395.2	329.2	413.7
Trial 2	0.21-100-0.80-YA-NP	-	18.1	38.1	82.1		145.2	409.2	343.6
	0.21-150-0.80-YA-NP	-	152.8	179.4	468.9	-	428.3	650.7	713.0
	0.21-150-0.80-NA-NP	-	161.2	372.5	715.9	-	444.2	517.2	1260.6
	0.21-200-0.80-NA-NP	-	238.8	392.6	809.2	-	486.1	805.7	3042.9
Trial 3	0.21-150-0.80-NA-YP	176.0	-	-	-	411.6	-	-	-
	0.21-150-0.80-YA-YP	255.9	-	-	-	887.1	-	-	-
	0.21-200-0.75-NA-YP	327.2	-	-	-	1102.1	-	-	-
	0.21-200-0.75-YA-YP	578.7	-	-	-	733. 7	-	-	-
Trial 4	0.21-100-0.80-YA-YP	22.5	167.2	92.1	-	59.3	585.9	399.0	-
	0.21-60-0.80-YA-YP	15.6	33.4	50.3	-	142.1	255.8	320.8	-

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Table 9. Percentages of permanent settlement derived from plate loading tests carried out on SC-CBMs laid in field trials.

	Identification code	s_p (%)			
		1 day	3 days	7 days	28 days
Trial 1	0.21-60-0.80-NA-NP	-	100	94.6	91.4
	0.23-60-0.80-NA-NP	-	99.5	96.1	93.3
	0.21-100-0.80-NA-NP	-	97.6	94.8	86.9
	0.23-100-0.80-NA-NP	-	98.5	91.3	91.1
Trial 2	0.21-100-0.80-YA-NP	-	73.8	100	71.0
	0.21-150-0.80-YA-NP	-	80.3	50.0	45.8
	0.21-150-0.80-NA-NP	-	74.6	33.3	56.3
	0.21-200-0.80-NA-NP	-	75.5	43.3	78.6
Trial 3	0.21-150-0.80-NA-YP	69.7	-	-	-
	0.21-150-0.80-YA-YP	55.6	-	-	-
	0.21-200-0.75-NA-YP	59.5	-	-	-
	0.21-200-0.75-YA-YP	21.1	-	-	-
Trial 4	0.21-100-0.80-YA-YP	82.4	85.1	84.3	-
	0.21-60-0.80-YA-YP	90.7	87.7	87.9	-

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Figure captions

Figure 1. Particle size distribution of aggregate fractions, RAP and mineral sludge.

Figure 2. XRD spectra of mineral sludge (untreated and treated with 6% quicklime).

Figure 3. SEM images and EDX spectra obtained on mineral sludge (untreated and treated with 6% quicklime).

Figure 4. Reference particle size distribution and Fuller model.

Figure 5. Construction of slabs in field trials.

Figure 6. Flowability of SC-CBMs laid in field trials as a function of cement dosage.

Figure 7. Compressive strength of SC-CBMs laid in field trials as a function of curing time (lower cement dosages: 60 kg/m^3 and 100 kg/m^3).

Figure 8. Compressive strength of SC-CBMs laid in field trials as a function of curing time (higher cement dosages: 150 kg/m^3 and 200 kg/m^3).

Figure 9. Resilient modulus of SC-CBMs laid in field trials as a function of stress state (lower cement dosages: 60 kg/m^3 and 100 kg/m^3).

Figure 10 Resilient modulus of SC-CBMs laid in field trials as a function of stress state (higher cement dosages: 150 kg/m^3 and 200 kg/m^3).

Figure 11. Typical stress-settlement curves obtained from plate loading tests carried out on SC-CBMs with a low cement dosage (100 kg/m^3).

Figure 12. Different types of stress-settlement curves obtained from plate loading tests carried out on SC-CBMs laid in field trials.

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